X-Ray Emission from Highly Charged Ions Colliding with a Relativistic Electron Beam in the SuperEBIT Electron Beam Ion Trap

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Abstract.
The high-energy electron beam ion trap SuperEBIT at the Lawrence Livermore National Laboratory allows the study of the x-ray emission from highly charged ions interacting with electrons with energy in excess of 200 keV. Radiation from ions as highly charged as Cf^{96+} has been produced this way. The facility is being used to investigate the contributions from quantum electrodynamics in heavy ions. Here the focus is lithiumlike ions, especially U^{89+}, which provide the opportunity for the most accurate test of QED in highly charged ions. We have also used the facility to measure the degree of x-ray line polarization as a function of the energy of the electron collision energy. For example, we have studied the linear polarization of the K-shell emission lines of Fe^{24+} for electron-impact energies high as 120 keV. A new area of research is the investigation of nuclear excitation by electronic transitions. This is the inverse process of internal conversion, where an atomic x ray is absorbed by the nucleus resulting in an excited nuclear state. We are planning to study this process in ^{189}Os using 217 keV atomic x rays generated in the interaction with a 196 keV electron beam.

INTRODUCTION

The electron beam ion trap is a modified electron beam ion source built to study the interaction of highly charged ions with an electron beam by looking directly into the trap.

The first electron beam ion trap, dubbed EBIT, was put into operation at the Lawrence Livermore National Laboratory in 1986 and is described in detail by Levine *et al.* [1, 2]. The machine initially was operated with a beam current of about 100 mA and energy of about 10 keV. This provided an electron density in the 10^{12} cm^{-3} range.

Because the first electron beam ion trap, dubbed EBIT, was designed as an x-ray source, spectroscopic instrumentation centered on analyzing the x-ray emission with broad-band germanium detectors and with high-resolution crystal spectrometers, notably flat-crystal spectrometers. This allowed the first measurement of electron-impact excitation cross sections of a highly charged ion [3], followed by measurements of dielectronic recombination rates [4, 5] and resonance excitation cross sections [6].

When compared to other x-ray sources at the time, e.g., tokamaks, beam-foil setups at heavy-ion accelerators, vacuum sparks, or laser-produced plasmas, EBIT was a relatively weak x-ray source. Focussing x-ray instrumentation was developed to collect more photons [7], resulting in high-resolution spectra useful for accurate wavelength determinations and QED studies [8] as well as measurements of innershell ionization

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cross sections [9] and energy-dependent electron-impact excitation cross sections [10].

The success of EBIT resulted in the construction of the second electron beam ion trap. This machine, dubbed EBIT-II, became operational at the Lawrence Livermore National Laboratory in January 1990. EBIT-II could operate with beam energies as high as 26 keV and beam currents as high as 250 mA.

Many high-resolution x-ray spectrometers were developed for this machine [11, 12, 13], which allowed many new atomic measurements, such as measurements of level-specific dielectronic recombination resonance strengths [14, 15], identification of magnetic octupole decay [16], and determination of radiative branching ratios [17]. A crystal spectrometer with resolving power $\lambda/\Delta\lambda = 68{,}000$ was employed to determine the ion temperature and measure the femto-second natural line width of electric dipole transitions of highly charged ions [18, 19]. In addition, absolutely calibrated monolithic crystals were implemented to make QED measurements of hydrogenic ions [20].

Fast-switching of the electron beam allowed to make the first measurement of the radiative lifetime of electric-dipole forbidden x-ray transitions in highly charged ions in the microsecond regime [21]. Development of the magnetic trapping mode, in which EBIT-II was operated without an electron beam [22], extended radiative lifetime measurements to electric dipole-forbidden x-ray transitions to many other highly charged ions [23, 24, 25].

In 2000, the 36-pixel array x-ray microcalorimeter devoloped by the Goddard Space Flight Center for the ASTRO-E space mission was added to the suite of x-ray instrumentation of EBIT-II [26]. It provided broadband x-ray detection capabilites coupled with a 10-eV spectral resolution and was used for various laboratory x-ray astrophysics measurements [27].

The successful operation of EBIT-II enabled the shutdown of EBIT in order to use parts for building a new, high-energy electron beam ion trap. This high-voltage machine commenced routine operation in January 1992 and was named SuperEBIT. The machine was designed for electron beam energies as high as 250 keV [28], and energies in excess of 200 keV were indeed achieved. With it any ion of essentially any element up to uranium could be produced, including bare uranium [29, 30]. The highest charge state to date is heliumlike Cf^{96+}, as discussed below. In other words, SuperEBIT allowed the production of highly charged ions that were heretofore only accessible by heavy-ion accelerators.

Because the ions were at rest in SuperEBIT (ignoring the small thermal motion of the ions), x-ray measurements were greatly simplified compared to similar measurements on accelerators. Moreover, measurements could be made, such as those of electron-impact excitation, that were impossible to do on accelerators.

X-ray studies on SuperEBIT included determinations of the $2s$ Lamb shift in lithiumlike thorium and uranium [31, 32], and measurements of the variation of the nuclear radii of ^{233}U, ^{235}U, and ^{233}U [33, 34]. These studies have culminated in the most accurate QED measurement of any highly charged ion [35]. This measurement was accurate enough to be sensitive to the two-loop self energy contribution [36].

Dielectronic recombination measurements were performed on U^{90+} and neighboring ions [37]. These measurements provided the first experimental evidence of the quantum mechanical interference between dielectronic recombination and radiative recombination.

The magnetic trapping mode, mentioned earlier, was developed on SuperEBIT [38, 39]. On SuperEBIT it was used to study the x-ray emission from very highly charged ions produced by charge exchange recombination [40]. Using pulsed gas-injection, charge-exchange-induced x-ray spectra were obtained with the magnetic mode for ions as highly charged as heliumlike U^{90+} [41].

Following the successful operation of EBIT, EBIT-II, and SuperEBIT, electron beam ion traps were constructed outside Livermore. The first two were built at Oxford, England, using the Livermore designs of EBIT-II. Some changes, however, were made. One of these machines was delivered to the National Institute of Standards in Gaithersburg, Maryland. A close copy of EBIT-II was built in the United States and delivered to the Institute for Plasma Physics in Berlin. Higher-energy machines were built at the University of Electro-Communications, Tokyo, and at the Albert-Ludwigs-Universität Freiburg, Germany (now moved to Heidelberg). Although all electron beam ion trap devices share common design principles, it should be noted that the performance characteristics of each device is unique. The performance characteristics vary from machine to machine in a similar fashion as, for example, one tokamak device differs from another.

As many of the new electron beam ion traps have been called "EBIT", we now refer to the orginal EBIT electron beam ion trap as EBIT-I to avoid confusion. EBIT-I has been put again in service at the Lawrence Livermore National Laboratory upon an internal move of the facility. At the same time, EBIT-II was moved to the Lawrence Berkeley Laboratory.

In the following we describe experiments performed with SuperEBIT. The experiments were carried out with relativistic electron beams in excess of 100 keV. This is an energy regime still unsurpassed at other ion traps. These energies have allowed us to study the x-ray emission of highly charged actinide ions and test predictions of quantum electrodynamics in novel ways. Our investigations are now shifting beyond uranium to elements as high as curium, berkelium, and californium. We have used the device to measure the linear polarization of x rays well into the relativistic regime. We are also preparing measurements to study nuclear excitation by atomic x rays.

Ten years have passed since SuperEBIT was first operated. This overview shows that many unique measurements at the forefront of highly charged ion research continue to be performed with this machine.

ACTINIDE SPECTROSCOPY

Very heavy elements are of great interest to fundamental atomic physics because they are associated with the strongest electric and magnetic fields found in nature. Uranium (element 92) has been of particular interest because it is the heaviest naturally occuring element. The strong nuclear fields and the finite nuclear extent of their origin affect the atomic levels considerably. The $1s$ Lamb shift in uranium is about 460 eV. In californium (element 98) it is close to 700 eV. Therefore, studying x-ray transitions from highly charged ions beyond uranium is one of the research areas we are pursuing on SuperEBIT.

The actinides are radioactive. Using large quantities of material would, therefore, contaminate our machine. However, only about 10^7 ions are needed to filled the SuperEBIT

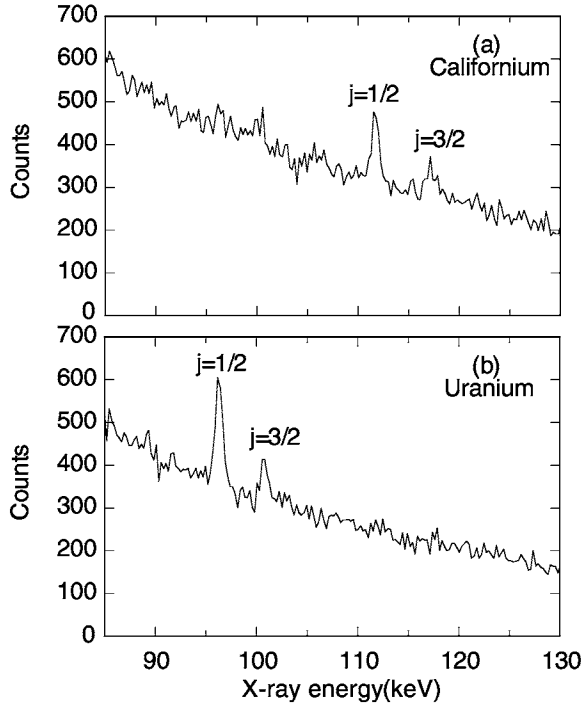

FIGURE 1. K-shell emission (a) of highly charged ^{249}Cf and (b) of highly charged ^{238}U recorded with a high-purity Ge detector. The label refers to the total angular momentum of the excited electron.

trap. This is such a small quantity that even radioactive elements can, in principle, be used in the device without appreciable contamination of the facility. Unfortunately, it is not easy to inject and trap only the amount of material needed to exactly fill the trap.

A method to inject trace amounts of radioactive material was described by Elliott and Marrs [42]. It relies on plating a small amount of radioactive material on the end of a thin wire. The wire is brought near the electron beam, where ion sputtering slowly transfers the material to the trap.

We have employed the wire method for injecting californium into SuperEBIT. A platinum wire was electrolytically coated with 5 ng (20 nC) of ^{249}Cf, and inserted into the SuperEBIT trap [43]. The trap was operated with a 250-mA electron beam at about 140–150 keV. A minimum of about 15 minutes was required before californium x rays were seen.

A K-shell x-ray spectrum collected within 30 minutes after insertion of the wire is shown in Fig. 1(a). The spectrum was recorded with a 5-cm diameter, 2-cm thick Ge detector. The spectrum shows one feature at 110 and a second at 114 keV. The lower-energy feature corresponds to $2s_{1/2} \rightarrow 1s_{1/2}$ and $2p_{1/2} \rightarrow 1s_{1/2}$ transitions; the higher-energy feature corresponds to $2p_{3/2} \rightarrow 1s_{1/2}$ transitions. For comparison, we show a spectrum of highly charged uranium in Fig. 1(b). In addition, we show the K-shell x-ray

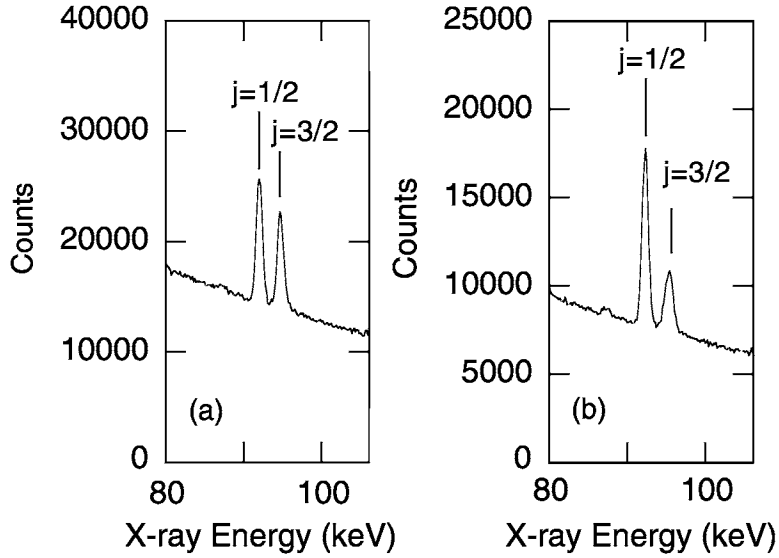

FIGURE 2. K-shell emission of highly charged thorium: (a) average charge around Th^{84+} and (b) average charge reaching Th^{88+}. The label refers to the total angular momentum of the excited electron.

of highly charged thorium in Fig. 2.

The intensity of the lower-energy feature is clearly higher than that of the higher-energy feature. This intensity ratio is very different from that observed in an x-ray tube where a neutral element is bombarded with an electron beam and the higher-energy feature, the so-called $K\alpha_1$ line, is about twice the size as the lower-energy feature, the so-called $K\alpha_2$ line. Only highly charged ions emit K-shell x rays where the lower-energy feature is as large or larger than the higher-energy feature.

The $j = 1/2$ feature dominates the intensity ratio of the two californium K-shell features in Fig. 1(a). This is a definitive signature that the californium was ionized as highly as heliumlike Cf^{96+}.

The thorium emission in Fig. 2 illustrates the dependence of this ratio on the charge balance. The charge balance in (a) was centered around C-like and N-like thorium, that in (b) was centered around He-like through Be-like thorium. The lower-energy feature clearly becomes larger as the charge balance shifts to higher charge states.

2*S* QED STUDIES

The $2p_{3/2} \rightarrow 1s_{1/2}$ K-shell transitions in the actinides have energies around 100 keV. By contrast, the corresponding $2p_{3/2} \rightarrow 2s_{1/2}$ L-shell transitions, have energies of a few keV. Since the QED contribution to the transition energy drops by a lesser amount than the overall transition energy, the fraction due to QED is actually higher in the

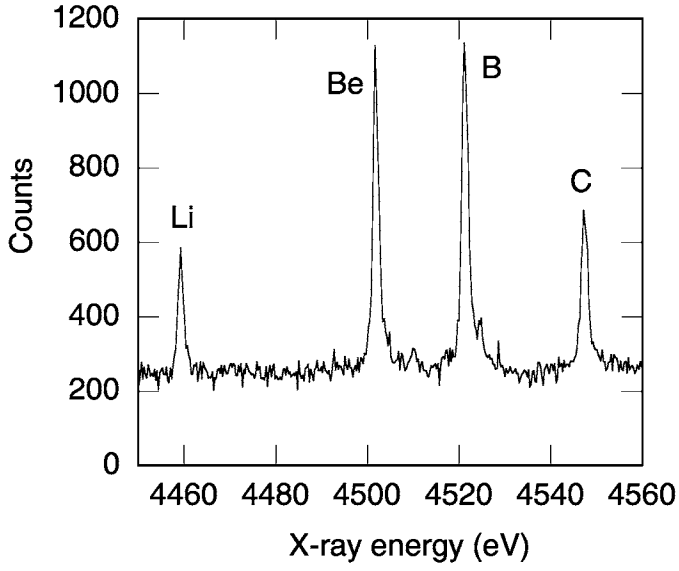

FIGURE 3. Crystal-spectrometer spectrum of the $2p_{3/2} \rightarrow 2s_{1/2}$ transitions from highly charged uranium ions in the energy region 4450 to 4560 eV. Transitions in lithiumlike, berylliumlike, boronlike, and carbonlike uranium are labeled by *Li*, *Be*, *B*, and *C*, respectively.

$2p_{3/2} \rightarrow 2s_{1/2}$ transitions. Moreover, the lower transition energies make it easier to measure these lines with current techniques. As a result, we have concentrated on measuring the $2p_{3/2} \rightarrow 2s_{1/2}$ transitions.

A spectrum of $2p_{3/2} \rightarrow 2s_{1/2}$ transitions in uranium near 4500 eV is shown in Fig. 3. An electron beam well in excess of 100 keV was required to produce the appropriate charge states. The spectrum not only shows the $2p_{3/2} \rightarrow 2s_{1/2}$ line in lithiumlike U^{89+}, it also shows the equivalent transitions in the neighboring charge states, berylliumlike U^{88+}, boronlike U^{87+}, and carbonlike U^{86+}. All of the $2p_{3/2} \rightarrow 2s_{1/2}$ transitions are affected by QED, which accounts for about 40 eV of the energy of these transitions.

Our measurements of lithiumlike $2p_{3/2} \rightarrow 2s_{1/2}$ transitions have been extended to bismuth, thorium, and uranium, as summarized in Table I. In uranium, we have made measurements for three different isotopes. The transition energy systematically increases for uranium isotopes with fewer neutrons and thus smaller nuclear radii. This clearly shows the strong influence of the nuclear size on the transition energy.

POLARIZATION SPECTROSCOPY

X-ray radiation generated by an electron beam is inherently polarized. We use this property to make explicit tests of polarization calculations. Because the degree of polarization depends on the relative strength of the populations of the magnetic sublevels, polariza-

TABLE 1. Measured $2p_{3/2} \rightarrow 2s_{1/2}$ transitions energies from different experiments.

Ion	Energy
$^{238}U^{89+}$	4459.37 ± 0.21 eV
$^{235}U^{89+}$	4459.43 ± 0.22 eV
$^{233}U^{89+}$	4459.63 ± 0.24 eV
Th^{87+}	4025.23 ± 0.14 eV
Bi^{80+}	2788.139 ± 0.039 eV

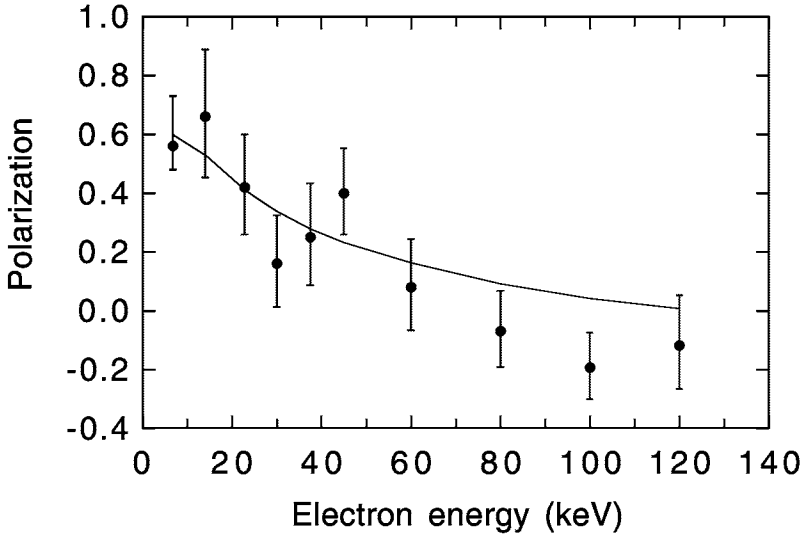

FIGURE 4. Polarization of the $1s2p\ ^1P_1 \rightarrow 1s^2\ ^1S_0$ resonance line in heliumlike Fe^{24+}. All data were obtained on SuperEBIT except the lowest-energy datum, which was obtained on EBIT-II. The solid line represents calculations obtained with the code of Zhang, Sampson, and Clark [48].

tion measurements test electron-impact cross section calculations on a more fundamental level than measurements of the total excitation cross section.

Calculations of the degree of linear polarization have been tested in several measurements with highly charged heliumlike ions on EBIT-I and EBIT-II [44, 45, 46]. These measurements tested the calculations near threshold for polarization.

The high electron collision energies achievable in SuperEBIT allow us to test the calculations in the fully relativistic regime. In Fig. 4 we show our measurement of the $1s2p\ ^1P_1 \rightarrow 1s^2\ ^1S_0$ resonance line in heliumlike Fe^{24+}.

Our measurements made use of the two-crystal technique for measuring polarization [47]. We employed two LiF crystals cut to the (220) and (200) planes. Measurements were made on SuperEBIT with beam energies between 14 keV and 120 keV. The figure

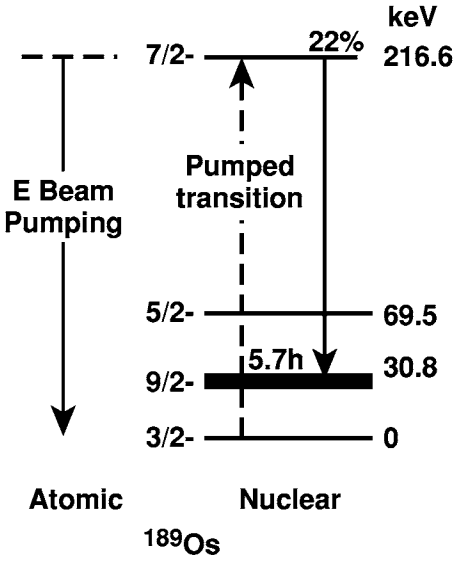

FIGURE 5. Energetics of the $^{189}Os^{75+}$ system.

also shows the value measured near threshold at 6.8 keV obtained on EBIT-II [45]. The results are compared to predictions obtained with the relativistic code from Zhang, Sampson, and Clark [48], and good agreement is found.

NUCLEAR EXCITATION BY ATOMIC X RAYS IN ^{189}OS

The relativistic electron beam energies achieved in SuperEBIT can also be used for novel nuclear physics measurements. We are beginning experiments to investigate nuclear excitation by absorbing atomic x rays. The aim of such atomic-nuclear interaction experiments is to determine the strength of the matrix element associated with the process dubbed NEET (nuclear excitation by electronic transition). NEET can be thought of as inverse internal conversion, i.e., the nuclear decay process in which a nuclear excited state decays by electron emission as opposed to gamma-ray emission.

Our experiments are centered on ^{189}Os. Here, the required degeneracy between the energy of an atomic transition and the nuclear energy level is accessible with our machine. The degeneracy is seen in Fig. 5, which shows the energy level diagrams for atomic and nuclear ^{189}Os. A beam electron is captured into an L-shell atomic level in heliumlike Os^{75+}. This capture releases an atomic x ray with energy equal to the sum of the electron beam energy and the binding energy of the captured electron. By tuning the electron beam to the right energy, the energy of the atomic x ray can be made to equal that of the 216.663-keV nuclear level indicated in Fig. 5. If the proper energy degeneracy is attained, the atomic x ray may excite the nuclear level via virtual photon exchange.

The 217-keV level gamma decays to the 31-keV metastable state (cf. Fig. 5) with a

decay half life of 5.7 hours. Detection of NEET is then achieved by detecting the decay of the 31-keV metastable state.

NEET has never been detected, and there are great uncertainties in the predictions of the matrix element. This makes these experiments a daring challenge.

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